TNO Physics and Electronics Laboratory

TNO Defence Research

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REMOTE LAND MINE(FIELD) DETECTION,
an overview of techniques

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TNO Defence Research

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REMOTE LAND MINE(FIELD) DETECTION,
an overview of techniques

author(s):

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date:

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MANAGEMENTUITTREKSEL

titel	:	DETECTIE VAN LANDMIJNEN EN MIJNENVELDEN OP AFSTAND, een overzicht van de technieken
auteur(s)	:	Drs. J.S. Groot, Ir. Y.H.L. Janssen
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Mijnen vormen een alledaagse dreiging op de moderne gevechtsvelden. Reden hiervoor zijn de hoge kosten-effectiviteit en de mogelijkheid om ze snel te leggen.Tijdens een conflict wordt de doorgang van troepen vertraagd door de aanwezigheid van mijnen(velden). Na afloop van een conflict belemmeren mijnen de wederopbouw van een gemeenschap. Cambodja is een voorbeeld hiervan. In dit land met 5 milljoen inwoners liggen nog 5-10 miljoen mijnen en ongeveer 10 procent van de bevolking heeft verwondingen tengevolge van een mijn. Om het voor militaire bevelhebbers mogelijk te maken om mijnen(velden) te omzeilen, te neutraliseren of te doorbreken is een "real time" detectie systeem voor mijnen of mijnenvelden essentieel.

De basis principes en sterke en zwakke punten van "real time" mijnen detectie met visuele, nabij-infrarode, midden en lange golf infrarode, microgolf radiometrische en radar systemen, worden gepresenteerd in de eerste hoofdstukken van dit rapport.
In het tweede deel van het rapport worden aanbevelingen gegeven voor een toekomstig systeem voor de detectie van mijnen. Deze aanbevelingen zijn gebaseerd op een literatuurstudie, de voornaamste conclusies van de activiteiten en onderzoeksgebieden van de verschillende RSG (AC243 SGE/CET geïnitieerd door panel IX, NAAG AC225) leden (landen) en overleg met en behoeften van DMKL, GEVST-MUN.
De voornaamste aanbeveling is de ontwikkeling van een prototype multi-sensor systeem voor op een voertuig. Dit is gebaseerd op de interesse die de "Genie" toont voor een dergelijk systeem, de kosten van een dergelijk systeem die factoren lager zijn dan voor een systeem dat vanuit een vliegtuig moet opereren en het op betrekkelijk eenvoudige manier kunnen testen en toepassen van sensor fusie. Veelbelovende technieken voor detectie systemen voor op een voertuig zijn:

1. passieve en actieve infrarood beeldvormende systemen,
2. microgolf radiometrie,
3. passieve en actieve visuele en nabij-infrarode discriminatie op basis van verschillen in golflengte afhankelijke reflectie-eigenschappen,
4. radar bodem en vegetatie indringend vermogen.

Voorgestelde tijdstappen in de ontwikkeling van een dergelijk sensor syteem voor op een voertuig zijn: een haalbaarheidsstudie, metingen vanaf een toren en ontwerp, ontwikkeling en het testen van een demonstratiemodel.

EXECUTIVE SUMMARY

title	:	REMOTE LAND MINE(FIELD) DETECTION, an overview of techniques
author(s)	:	J.S. Groot, Y.H.L. Janssen
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Minefields form a common threat on the modern battlefield. Reasons are the high cost-effectiveness, and the possibility to lay them quickly. During a conflict the passage of troops is delayed by minefields. After a conflict, minefields hamper the development of a community seriously. An example is Cambodia. There are currently 5-10 million mines left in this country with 5 million inhabitants. About 10 percent of the population has mine induced injuries.
To enable military commanders to plan their movements to circumvent the mines (or minefields) or to allocate/employ mine neutralisation/breaching assist to clear a safe route through a minefield, a (near) real time land mine or minefield detection system is essential.

The first chapters of this report present the basic principles and strengths and weaknesses of mine detection of such a system with visual, near infrared, midwave infrared, longwave infrared, microwave radiometric and radar systems.
The second part of the report presents recommendations for future mine detection systems. These recommendations are based on a literature survey, main conclusions from the activities and research of the different RSG (AC243 SGE/CET initiated by panel IX, NAAG AC225) member countries and the discussions and demands of the DMKL, GEVST-MUN.
Main recommendation is the development of a prototype vehicle mounted multi-sensor system since the "Genie" expressed its interest in such a system, it is cheaper than an aircraft mounted system, and sensor fusion can be tested and applied on such a system. Promising techniques for a vehicle mounted detection system are:

1. passive and active infrared imaging,
2. microwave radiometry,
3. passive and active visual and near infrared wavelength discrimination,
4. radar ground and vegetation penetration.

Proposed time steps in the development of a demonstrator of a vehicle mounted mine detection system are a feasibility study, tower measurements and design, construction and testing of a demonstrator.

CONTENTS

1 INTRODUCTION

Minefields form a common threat on the modern battlefield. Reasons are the high cost-effectiveness, and the possibility to lay them quickly, for example from an airplane. During a conflict the passage of troops is delayed by minefields. After a conflict, minefields hamper the development of a community seriously. An example is Cambodia. There are currently 5-10 million mines left in this country with 5 million inhabitants. About 10 percent of the population has mine induced injuries.

NATO member countries recognised the need for a (remote) detection system for mines and minefields and followed a request of the Defence Research Group (DRG), panel IX of the NAAG, AC225 in September 1991. A Special Group of Experts for Combat Engineering Technology (SGE/CET) was established under AC243. The SGE identified two fields of research to pursue: Remote Detection of Minefields (RSG1) and Stand-Off Neutralisation of Minefields (RSG2).
As usual, definitions, objectives etc. of the RSG1 are given in a document called "Terms Of Reference" (TOR). The start of RSG1 was marked by the acceptance of the TOR by the DRG (NATO Defence Research Group) in March 1993. The overall duration of the group will be 4 years. The RSG1 name definition given in the TOR is:

<u>Remote Detection of Minefields</u>:

"procedures and techniques used to locate, classify and report the presence and extent of minefields where the detector system is located separately from the minefield, usually well beyond the lethal range of mines, and where the operator may or may not be located separately from the detector system."

The objective as stated in the TOR is:

"The main objective of this RSG is to investigate the feasibility of a remote minefield detection capability which will enable commanders to plan their movements to circumvent the minefields or to allocate/employ mine neutralisation/breaching assist to clear a safe route through the minefield."

2 HISTORY OF THE PROJECT

Already in 1992 the DMKL ("Directorate of Material of the Royal Netherlands Army") initiated a project (A92KL700) which included the following:

- attendance of the biannual RSG meetings
- literature survey
- basic study of the applicability of mathematical morphological techniques
- initiation of possible follow-up study, based on results of the foregoing parts

The work is carried out by J.S. Groot (TNO-FEL), and is finalised at the end of 1994. Because the expertise of Groot lays mainly in the field of microwave remote sensing, a parallel project (A93KL645) was spawn of which covers the ultra-violet, visual and (thermal) infrared wavelengths. This project led by Y.H.L. Janssen (TNO-FEL) contains:

- basic study of the applicability of UV, visual and active and passive infrared mine detection
- literature survey
- basic experiments and model calculations
- future attendance of biannual RSG meetings concerning close-in detection
- initiation of possible follow-up study, based on results of the foregoing parts

Up till now, four RSG meetings have been attended (December 1992, June and December 1993, June 1994). RSG member countries are Canada (CA), USA, United Kingdom (UK), Germany (GE), Denmark (DK), France (FR), Italy (IT), Belgium (Be) and The Netherlands (NL). These are the main conclusions from the minutes of these meetings by the Netherlands attendant:

- CA, USA, GE and UK have the most comprehensive research programs.
- CA investigated a large subset of possible sensors, but now concentrates on infrared sensors and on image analysis.
- the USA research is oriented towards the development of an operational minefield detection system.
- GE initiated two contracts concerning multi-sensor systems.
- UK's emphasis is on novel microwave sensors.
- DK is in pretty much the same situation as NL, and starts a small research program in 1994.
- CA, UK and DK research is mainly carried out by the national army instead of private companies, which makes co-operation with one of these countries the easiest.
- FR did not yet present their research program, although it is said to have a high priority.
- IT attended only 2 meetings, BE none. Both countries did not present their research programs.

Note that these conclusions are only a subjective interpretation based on what has been told during the RSG meetings, and might not reflect the actual situation accurately.

The TOR objective concerns (near real time) minefield detection during a conflict. This type of detection is thought to be carried out from an UAV (Unmanned Aerial Vehicle), flying at low altitude of typically 100 meter. On ground of the information gathered by the UAV, the commander decides to take an alternative route to avoid, or to clear part of the minefield. NL emphasised the importance of non-real time detection of single mines after conflicts, based on the recent experiences during UN operations (e.g., in Cambodia).

Although close-in detection is not formally part of this RSG's work terrain, sometimes the subject is touched during the meetings. This is due to the overlap between some close-in and remote detection techniques. For example, detection from a vehicle with an infrared camera looking 20 meters forward can be regarded as close-in as well as remote detection. During the June 1994 meeting the question was posed whether certain types of close-in detection should possible become part of this RSG, or should be incorporated in a new RSG. The decision is foreseen to be taken during the December 1994 meeting.

The results of the literature survey are given in the appendices A-H of this report, which include abstracts of the papers and reports read. For reasons of convenience and to be able to use the appendices seperately some abstracts appear in several appendices.

3 IMAGING SENSORS FOR THE DETECTION OF MINES AND MINEFIELDS

The problem of mine and minefield detection is a difficult one, for the following reasons:

- mines are small (5-30 cm diameter)
- mines have a variety of shapes
- mines can be metallic or non-metallic (e.g., plastic or wooden)
- mines can be buried or laid on the surface
- minefields can be patterned or non-patterned

Detection of a single mine is more difficult than that of minefields. In general, un-buried mines are easier to detect than buried ones (not taking into account possible surface disturbances due to the laying process). Similarly, patterned minefield detection will be easier than its non-patterned counterpart. In addition, large mines will be easier to detect than small ones.

Each of the sensors discussed next has its typical strengths and weaknesses with regard to mine(field) detection. The emphasis will be on these characteristics instead of on technical details. A summary of the (dis)advantages of each sensor system is given in table 5.1.

3.1 Radar

References in appendix A related to radar are [A1-A20]. They treat close-in as well as remote detection and buried as well as surface laid mines.

A radar transmits electromagnetic radiation with a wavelength ranging from millimetres (W-band or mm-radar) to meters (P-band radar), or even larger. It receives the radiation back-scattered by objects which intercepted part of the incoming radiation. The amount back-scattered gives the Radar Cross Section (RCS) of the object. The RCS of a mine relative to that of the background determines the detectability of the mine.

The most important radar characteristics are:

- wavelength. Longer wavelengths penetrate (soils) deeper.
- polarisation (transmit and receive antenna polarisation). Conventional radars have a single transmit and receive polarisation. Polarimetric radars act as if they measure with each possible transmit/receive polarisation combination simultaneously.
- spatial resolution. This is the size (in m^2) of the smallest detail which can be resolved by the radar. It always exceeds the wavelength squared.
- radiometric resolution (the smallest change in RCS which is still detectable).

The RCS of a mine (omitting the background) depends on:

- its size. The larger a mine, the higher its RCS (assuming only a change of size, not of wavelength, viewing direction etc.).
- the material it is made from. Metallic mines have generally a higher RCS than non-metallic ones.
- the radar wavelength. The RCS is higher for smaller wavelengths.
- the radar polarisation. The RCS varies quite unpredictable with the polarisation.
- the viewing direction. The higher the mine size to wavelength ratio, the faster the RCS varies with the viewing direction. Cylindrical mines have the highest RCS when viewed from the top or the side (due to specular and two-bounce reflection, respectively).
- spatial resolution, if the resolution is smaller than the mine.

Buried mines have generally a reduced RCS, depending on the depth under the surface (surprisingly, some of the measurement results in [A20] indicate an enhanced RCS).

The *average* RCS of the background depends on:

- the radar spatial resolution ("size of the background"). The larger (worse) this resolution, the higher the background RCS.
- its moisture content. The larger the moisture content, the larger the RCS.
- its surface roughness. Increasing the roughness increases the RCS.
- the radar wavelength. The RCS is higher for smaller wavelengths.
- the radar polarisation. The RCS is smallest for HV, VH, LC-LC and RC-RC polarisation for backgrounds with a near unit scattering matrix (H= Horizontal, V= Vertical, RC= Right Circular, LC= Left Circular). Examples are smooth bare soils and grassland.
- the viewing direction, but in a more or less predictable (smooth) way. It is highest for normal incidence (specular reflection).

Note that the points above determine the *average* RCS of the background. Generally, the measured background RCS varies wildly (in space and time), due to the coherent nature of the radiation transmitted by the radar. For example, the average RCS of a square meter of grass might be 0.1 m^2 but measuring it some time later, or moving the radar "spot" a few meters away might give a value of 0.2, 0.05, 0.28 or ? m^2. This particular phenomenon is known as "speckle", and has noise like characteristics. The amount of variation is precisely known, but can only be suppressed by averaging measurements done at different times or locations. This affects the measurement speed or spatial resolution, respectively speckle is inherent to the use of an instrument which uses coherent radiation, like radar. Moisture and roughness variability in space contribute to the total RCS variation.
Because averaging is inevitable, one should strive for the highest possible resolution, probably below 20 cm. This limits the wavelength below this value, because the resolution can never be better than (be below) the wavelength.

From the dependence of mine and background RCS on the various quantities mentioned, it follows that no single radar will be able to detect all mine types under all circumstances. For example, buried mine detection would require a long wavelength radar due to its ground penetration capability, but this limits its applicability to the largest of mines, because its spatial

resolution exceeds the wavelength squared. This in turn increases the minimum background RCS.

Most studies point out that an imaging radar system with the best performance for surface laid mines should have a high frequency (35 or 100 GHz), a spatial resolution smaller than the mine size and be downlooking (i.e., look direction perpendicular to the flat mine tops, which are assumed to be oriented near horizontally). For a real aperture radar (for which the spatial resolution is linearly proportional to the radar-mine distance), this implies that the system should be flown at an altitude below 100 m. The detection probability will depend heavily on background characteristics. The high frequency causes such a system to be useless for buried mine detection. The use of a polarimetric system is recommended, in order to achieve the highest mine-background contrast.

Long wavelength (> 10 cm) radars are able to penetrate the surface to depths at which mines are typically buried, suggesting their utility for buried mine detection. A serious drawback of such a large wavelength is that clutter reduction by spatial averaging is impossible.
However, all literature studied indicated that the detection of buried mines is harder than the detection of the same mines on top of the surface. And even the latter is only possible under the most favourable conditions (small background RCS and high spatial resolution).

3.2 Microwave radiometers

References related to microwave radiometers are presented in appendix B [B1-B11].

As opposed to radar, a radiometer does not transmit radiation. A radiometer receives the natural radiation emitted and reflected by all objects (the former is therefore called an active, the latter a passive system), at a wavelength in the radar range. The amount received gives the radiation temperature T_r. This temperature of a mine relative to that of the background determines the detectability of the mine.

The most important radiometer characteristics are:

- wavelength.
- polarisation (of the receive antenna).
- spatial resolution.
- radiometric resolution (the smallest detectable change of the radiation temperature).

The radiation temperature of a mine (omitting the background) depends on:

- the radiometer wavelength. T_r increases with the wavelength.
- the radiometer polarisation.
- the viewing direction. This depence is weak compared to that of radar measurements.
- the physical temperature of the object. The higher this temperature, the higher T_r.
- the material it is made from. Metal mines have a much smaller T_r than plastic mines.

- the "sky temperature". This is because the radiometer not only receives radiation emitted by the mine, but also radiation reflected from its surroundings, including the sky. This dependence is largest for highly reflective metal mines. The sky temperature depends in turn on cloud occurrence.
- its depth under the ground surface, for buried mines.

The radiation temperature of a background depends on:

- soil moisture. T_r decreases with increasing moisture.
- soil roughness. T_r increases with increasing roughness.
- radiometer wavelength. T_r increases with increasing wavelength.
- radiometer polarisation. It is higher for vertical than for horizontal polarisation.
- incidence angle (angle between viewing direction and the vertical). For incidence angles below 30 degrees the dependence is small.

The measured T_r of a mine in a background depends on the beamfill factor, which is the mine area divided by the spatial resolution. The larger this beamfill factor, the larger the difference (= contrast temperature) between T_r and the background only radiation temperature.

As opposed to radar, radiometer measurements do not suffer from "speckle". However, because the natural radiation emitted is essentially noise, one has to use a large bandwidth and integration time to achieve a sufficient high radiometric resolution.

Ref.[B8] presents measurements at 35 and 90 GHz (86 and 33 mm wavelength, respectively) performed with a scanning vertically polarised radiometer, operated from a roof (Figure 3.1). The next results and figures are copied from this reference.

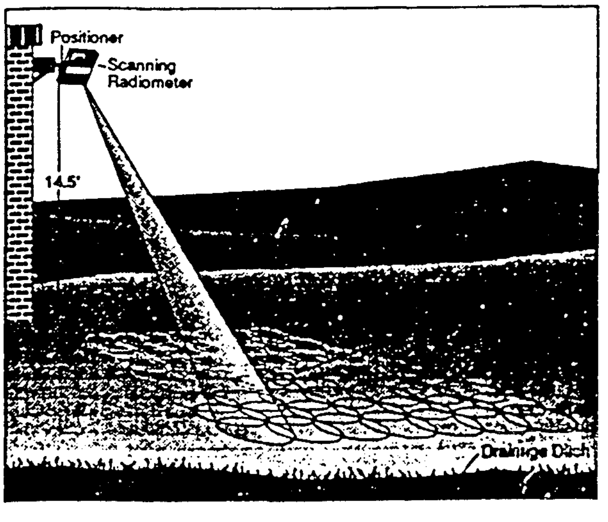


Figure 3.1: A sketch of the experimental set-up.

Figure 3.2 shows two consecutive scans over a metallic mine (located at scan angle of 0 deg.), clearly proving its detectability. The difference between the two is due to the limited calibration

accuracy. The contrast temperature T_C is approximately 270 K - 50 K = 220 K for this particular case.

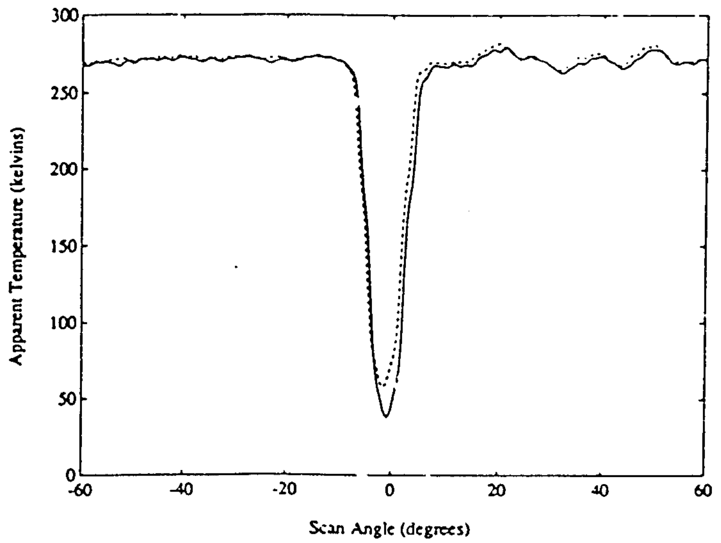


Figure 3.2: *Two consecutive scans at 90 GHz.*

Figure 3.3 shows T_C of a metallic target as a function of look angle (= 90 degrees - incidence angle).

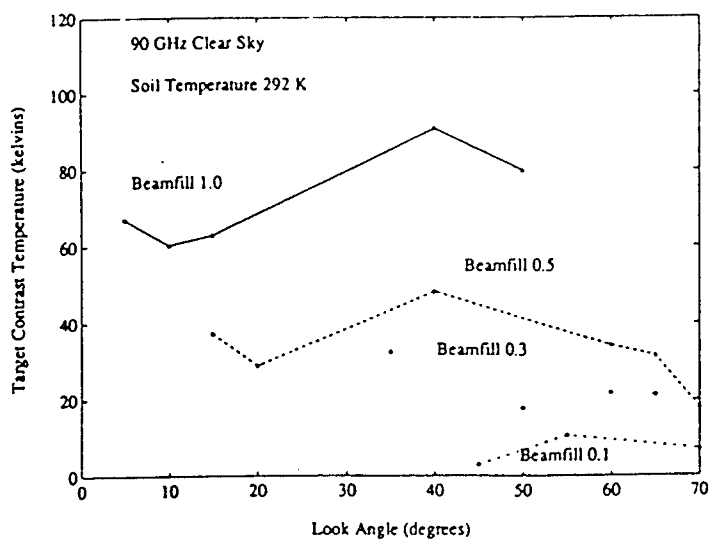


Figure 3.3: *Metallic target contrast as function of look angle for constant beamfill factor.*

T_C depends only moderately on the look angle. As noted before, the contrast temperature depends on the beamfill factor. Figure 3.4 presents data on the relation between the beamfill factor and the contrast temperature, in conjunction with an antenna model fit. This graph proves that detection is possible (the contrast temperature exceeds a few degrees Kelvin), even if the mine is smaller than the spatial resolution (beamfill factor below 1).

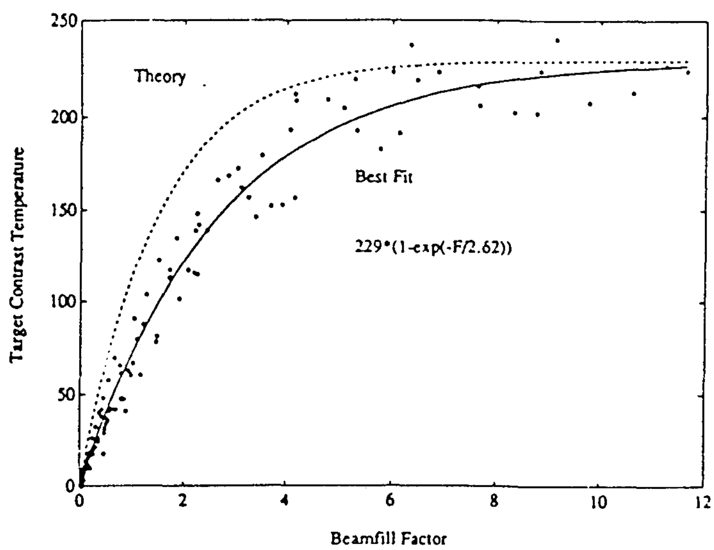


Figure 3.4: *Metallic target contrast temperature from the Gaussian antenna model compared with the 90 GHz clear sky data. The dashed line is the Gaussian model and the solidline is the best fit.*

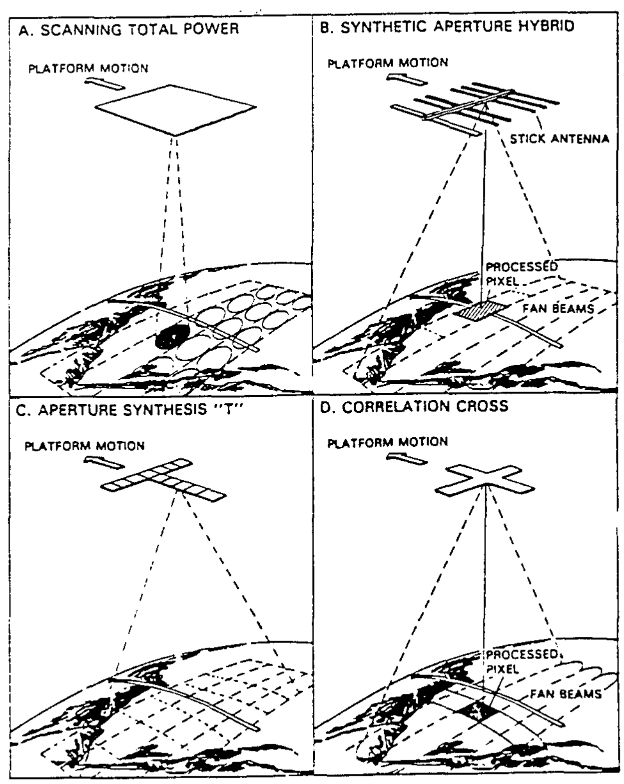


Figure 3.5: *The panels illustrate several different imaging radiometers: (a) A scanning total power radiometer; (b) A hybrid which achieves resolution along track with a real aperture and uses aperture synthesis to obtain resolution across track; (c) A radiometer which employs aperture synthesis in both dimensions with the antennas arranged along the arms of a "T"; and (d) A radiometer in which the scene is mapped by correlating the beams formed by each arm of a "cross" (from [B11]).*

From this study it is clear that metallic objects which are not obscured by vegetation or any other covering are readily detectable. The system recommendations done in this report on ground of the measurements are that a helicopter based system resembling the roof based one is feasible. Key parameters are: frequency 90 GHz, antenna diameter 30 cm, nadir spatial resolution 0.4 m^2, radiometric resolution 1 K, flying height 15.2 m, nadir swath width 50 m, flight speed 30 km/hr and a weight of 70 kg.

It would be interesting to investigate the use of a synthetic aperture antenna like that of [B10-B11]. Figure 3.5a illustrates the principle of image formation by a real aperture system, like the helicopter based one above. The image is formed by cross-track scanning, and the movement of the platform. By using a synthetic aperture antenna like that of figure 3.5c, one doesn't need to scan cross-track like in figure 3.5a. The T-shaped antenna consists of several (small) antennas. Image formation is accomplished by processing the data from different antenna pairs with different spacing. The highest (best) spatial resolution is approximately the same as that of an antenna with equal physical dimensions. However, because the T-shaped antenna array is completely filled with antenna's, it will be lighter (this is especially advantageous for operation from space). A drawback is that the radiometric resolution drops because of the reduced physical collecting area (sum of the individual real apertures). It can be shown that this resolution is nevertheless only marginally worse than that of a real aperture system, because the synthetic aperture system does not scan [B11]. This increases the integration time. Note that unlike the SAR case, a radiometer's synthetic aperture does not exceed the physical antenna size.

3.3 Visual and near infrared

References related to detection of mines with visual and near infrared systems are presented in appendix C [C1-C10].

A covert, all day, all weather, real time sensor is required for detection of mines and minefields. The visible and near-infrared (NIR) wavelength range does not always fulfil these conditions since:

- passive imagers in these wavelength bands can only be used during day-time
- mines are more easy to camouflage (e.g. with paints) in these wavelength ranges
- the transmittance in these ranges is often poor compared to transmittance in other wavelength ranges

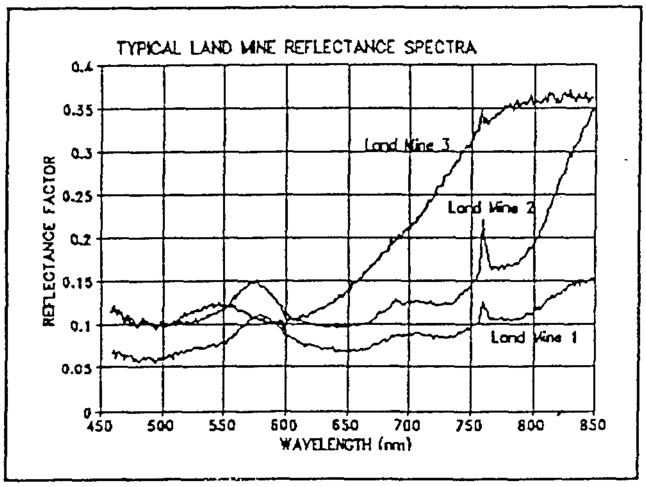
Nevertheless, detection in the visual and NIR bands has also several advantages [C7]:

- it can be done passive
- these sensor systems have often a high spatial resolution and visible texture
- most systems are real time
- it is a mature technology
- the sensors are often low cost compared to sensors active in other bands
- the sensors are often compact compared to sensors active in other bands

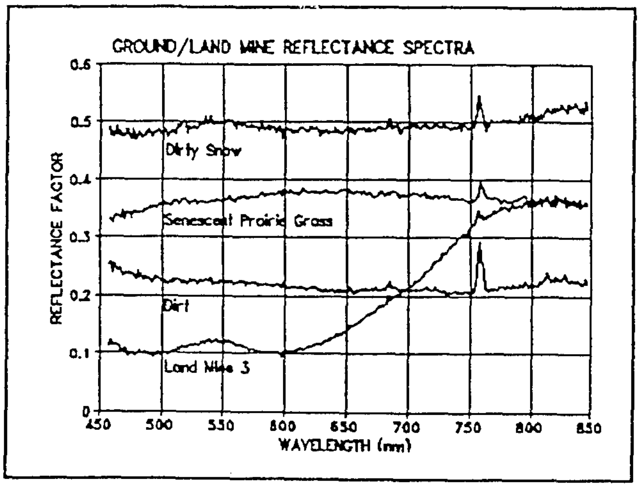
Because of these advantages most future mine detection systems will consist of a sensor active in the visible and NIR band, complementing a sensor active in another band. Potential visual and NIR imagers are 8- and 12 bits linear CCD (Charge Coupled Devices) cameras, active NIR laser scanners, and LLLTV (Low Light Level Television). These different potential systems and aerial photography are discussed separately in the following section.

<u>8- or 12 bits linear CCD camera, possibly combined with several spectral filters:</u>

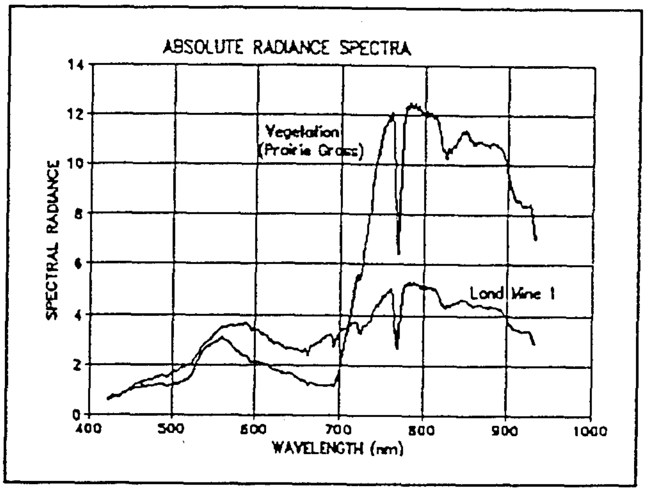
In the visible (wavelength range: 400-700 nm) and NIR (700-1300 nm), mines are often camouflaged with paints, but exact spectral matches occur only at a few points in the spectrum. Bands where large differences in reflectivity occur vary in centre position and width for different mines, mine paints and background types. Figure 3.6 presents vegetation and land mine spectra.



(a)



(b)



(c)

Figure 3.6: (a) typical land mine spectra, (b) typical ground/land mine reflectance spectra, (c) absolute radiance spectra.

Although these spectra show many similarities, such as a green reflection peak (at 550 nm), a red reflection dip (at 680 nm due to the absorption by chlorophyl) and an increased signal in the NIR, there are many differences that could be used for future analysis.
Overall vegetation spectra exhibit a much more pronounced absorption in the red (680 nm) with a sharp corner (700-730 nm) where the signal begins to strengthen in the NIR, as can be seen in figure 3.6c. The signal also becomes much more pronounced in the NIR vegetation spectra than the land mine spectrum. From [C10] it follows that five broad wavelength ranges are sufficient to determine differences between spectral data of mines (also camouflaged and painted) and backgrounds. These conclusions are based on spectral data of 11 minerals, 4 types of rocks, 5 types of soil, 33 types of vegetation and 5 types of mines. The resulting wavelength bands are:

- 0.596 - 0.732 μm
- 0.734 - 1.238 μm
- 1.502 - 1.750 μm
- 1.998 - 2.130 μm
- 2.134 - 2.290 μm

From [C9] and [C10] it follows that it would be interesting to investigate the possibility of mine and minefield detection with an 8 bits CCD-camera or a 12 bits linear CCD in combination with several band filters (visual and NIR). An advantage of such a system is that it gives real time images (and detections), that it is relatively low cost, passive and has a high spatial resolution.

Active NIR scanner:

The image of an active NIR scanner shows the retro-reflected NIR radiation that is generated by a source on that same system itself or another man-made source. Often a laser is used as the radiation source, but active illumination with a lamp is also possible.
Advantages of an active NIR laser scanner are:

- a high spatial resolution,
- construction of 3D images possible: information on the distance between the imagers and the object is measured,
- can be used during day as well as night time,
- no image clutter due to shadow,
- it can be side- or down-looking,
- large area coverage.

Disadvantages of active NIR laser imaging system are the speckle in the images and the operating problems with a moving platform e.g. a vehicle or airplane.
Recent developments show that these problems can be reduced to an acceptable level. Together with the above mentioned advantages it is clear that an active NIR laser scanner is a promising technique for the detection of mines and minefields. Still, a lot of research has to be done in this field. Bi-directional reflectance data of mines have to be collected. Of equal importance is knowledge of military paints. Experiments should investigate different mine shapes and

textures, the effects of water or dirt on mine surfaces, and the visual and NIR reflectance and statistical distribution of various materials within the natural environment.

Low Light Level Television (LLLTV):

Another possibility of the usage of the visible and NIR wavelength band is by means of LLLTV. An advantage of these systems is that they can be used during night time. A disadvantage of these systems is that they generally have a poor discrimination compared to for example thermal infrared imagers and that the discrimination decreases with decreasing intensity of the light. Therefore these systems are less suited for the detection of mines and minefields.

Aerial photography:

Conventional aerial photography will continue to have important applications with respect to detailed mapping of minefields. However, a serious drawback is the absence of a digital output.

3.4 Mid-wave and long-wave infrared

References in appendix D [D1-D20] relate to mine detection in the mid-wave (MWIR) 3-5 μm band and the long-wave (LWIR) 8-12 μm band. Close-in detection as well as remote detection and surface laid and buried mines are treated in these references.

Figure 3.7 illustrates the major features of energy transport from the scene to the IR imager. Scene radiation along a line of sight (LOS) from the source to the imaging system arises from four mechanisms:

- self emission,
- transmission of emissions from objects behind the source,
- reflection of remote emissions from objects in front of the source,
- scattering and/or diffraction of all these from outside the LOS into the LOS by the intervening atmosphere.

All these phenomena are angular dependent, so that the IR appearance of a differential element of a source's surface may depend on the viewing angle relative to the surface normal and on the angles of external sources relative to the surface normal.

The infrared contrast of natural terrain features and man-made objects as mines is strongly dependent on the strength of insolation. In an infrared image the contrast (e.g. between a mine and it's background) is specified by the apparent temperature difference between the source (e.g. mine) to the apparent temperature of its background (e.g. soil).

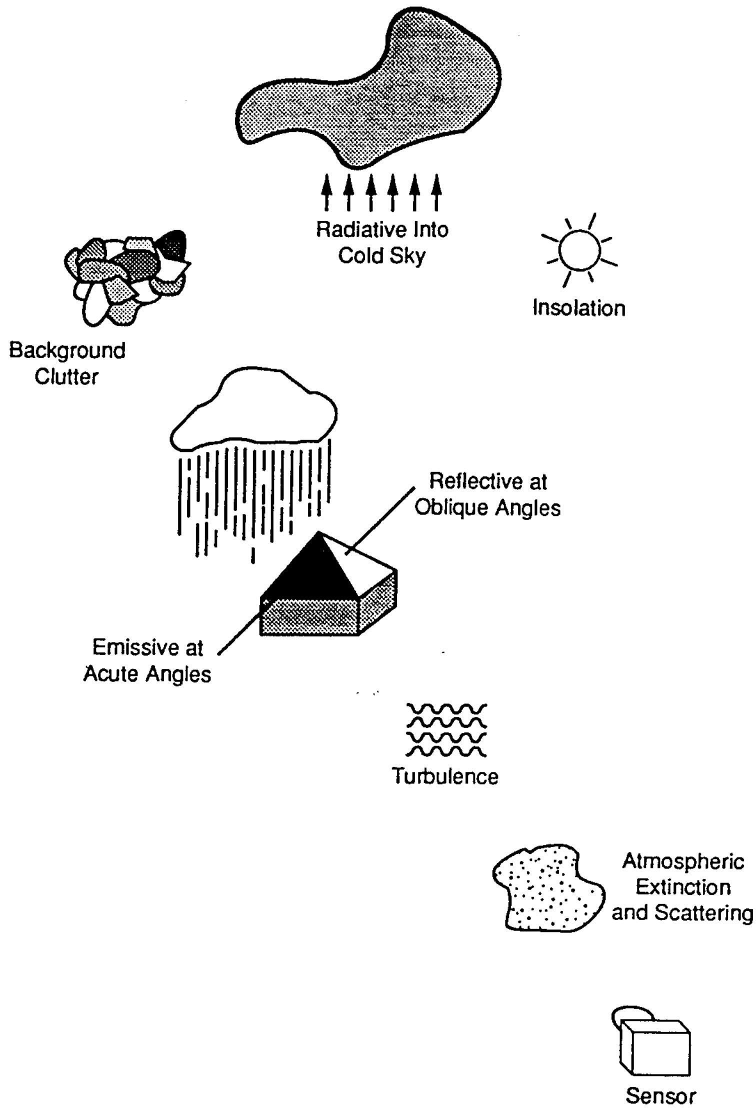


Figure 3.7: *IR imaging characteristics [D18].*

Due to atmospheric conditions (figure 3.8) and sensor capabilities the MIR wavelength band is divided into two bands, the MWIR 3-5 μm band and the LWIR 8-12 μm band.

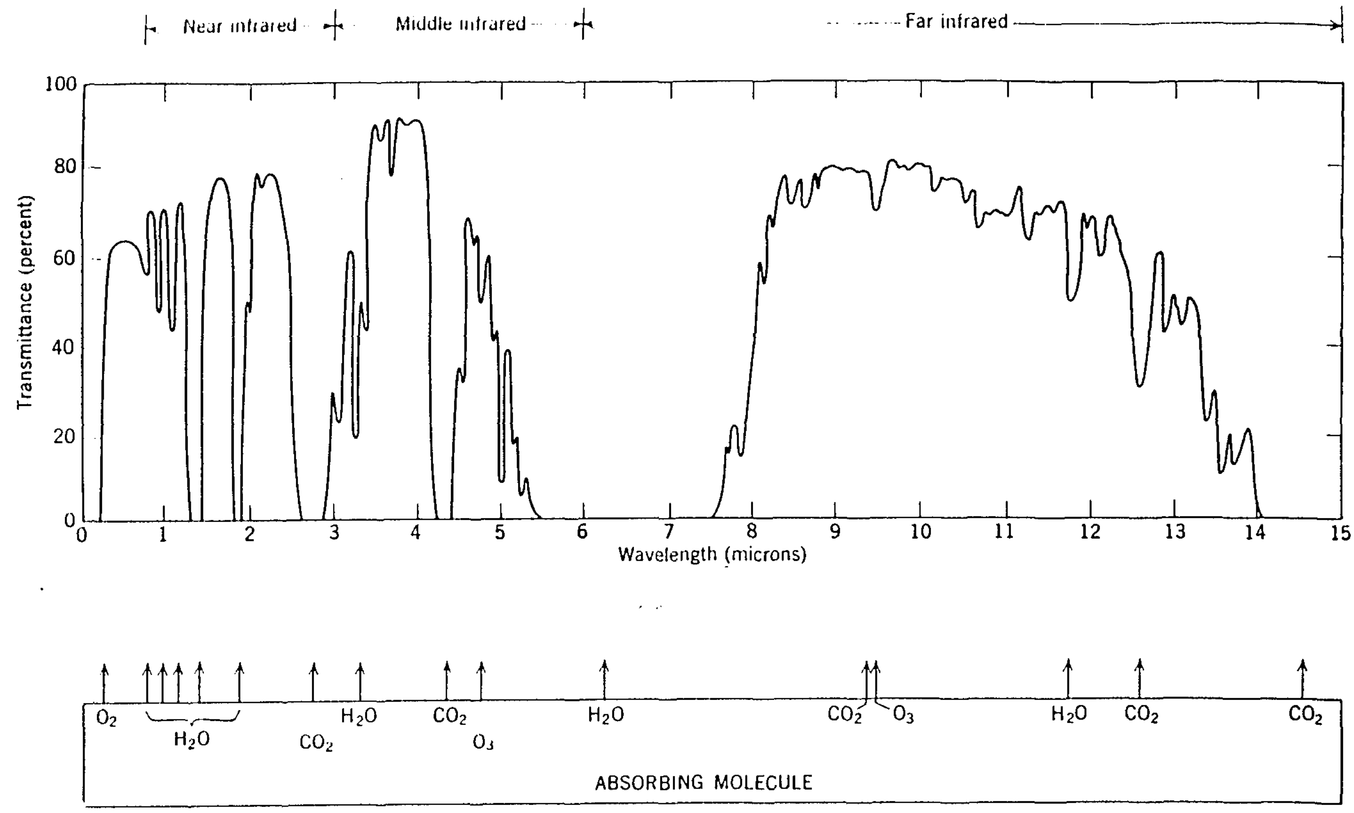


Figure 3.8: *transmittance of the atmosphere for a 6000 ft horizontal path at sea level containing 17 mm of precipitable water.*

Good performing IR imaging systems can be divided into two main categories: IRLS (Infrared Line Scanning) systems and FLIR (Forward Looking Infrared) systems.

An IRLS system is an imaging device that forms images by successive scans of a rotating mirror. The scans are transverse to the line of flight or drive of the vehicle carrying the IRLS. The second scan needed for a two-dimensional image is provided by forward motion of the vehicle. A for mine and minefield detection very useful type of a IRLS is a pushbroom scanner [D19]. If a vertical scanning mechanism is added to the IRLS a form a FLIR system is created.

FLIR systems [D20] are commonly divided into two broad categories: scanning and staring. For the staring FLIR systems often Focal Plane Arrays (FPA) are used. Such an FPA is a detector array of e.g. 480 x 640 detectors. In general, the larger the number of detectors, the higher the sensitivity and the smaller the minimum detectable contrast of the thermal imager. The high sensor sensitivity is ideal for the detection of mines, as can be seen in figure 3.9.

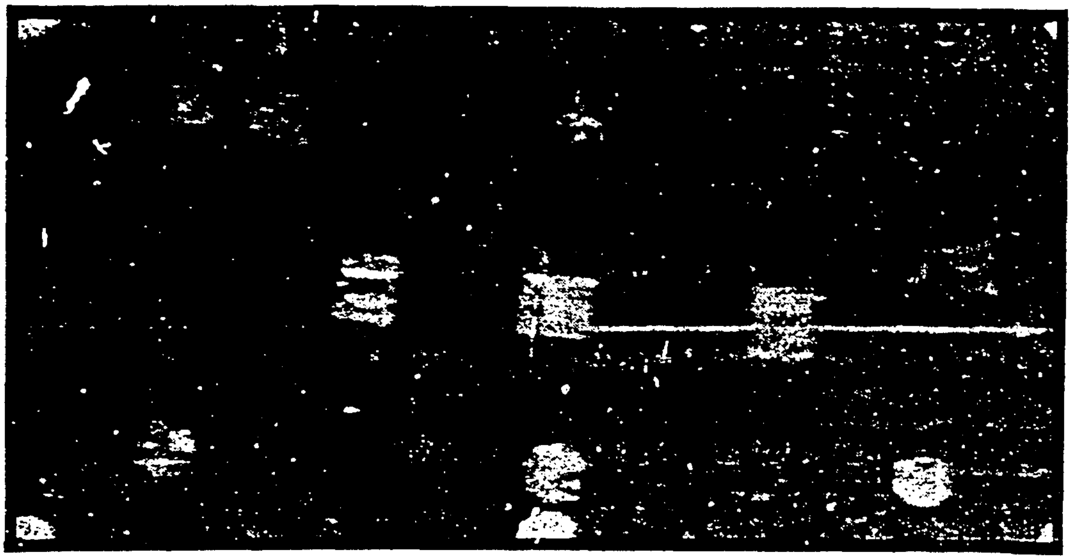


Figure 3.9: Active IR image of PM-60 and TMB-D mines on a soil background [D15].

Apart from the division of IR systems in IRLS's and FLIR's one can divide them in active and passive systems. Active IR systems obtain an image of a scene by measuring the exact reflected IR radiation which was generated by an emitting source on that same system itself. This principle is called retro-reflectance. A well known and good performing active MIR system is a high resolution CO_2 laser system with a nominal wavelength of 10.6 μm.
A passive IR system does not use such an emitting source on the system and creates an image that is only formed by the factors shown in figure 3.7.
Differences, advantages and disadvantages of active and passive IR systems are presented in table 3.11.

<u>Detection of a mine or mines depends on:</u>

In case of passive sensors:

- the difference in apparent temperature between a mine and its background. The apparent temperature is a combination of the emission and reflection of the TIR radiation and is determined by the heat balance of that certain element. The apparent temperature depends on material parameters e.g. reflection coefficient and environmental and meteorological conditions as sun illuminance, relative humidity and environmental temperature. Due to the heat exchange of the earth's surfaces and the atmosphere, twice per day a thermal "washout" (minimum contrast between mines and their backgrounds) may occur. Optimal passive TIR detection of mines times should be done on a time of day where the thermal contrasts are high. Nevertheless, the period of a day that a thermal "washout" appears becomes much smaller due to the good performance of modern TIR camera's. It is already possible to detect very small temperature differences, IR imagers with FPA's can have NETD's (Noise Equivalent Temperature Differences) of up to 0.03 °C.

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- The spatial resolution: the IFOV (Instantaneous Field Of View) of a passive TIR camera should at most cover the size of a mine. For example detection of a 30 cm mine obligates use of a sensor syetm with a spatial resolution of less than 30 cm. For a system with a FPA it is possible to detect mines of approximately 5 cm at a distance of 500 meters. Typical IFOV's of a system with a FPA are .2 mrad.
- Clutter: detection of a mine or mines with a passive TIR imager not only depends on the IFOV and NETD of that imager but also on the clutter in the background. Mines in an uncluttered background are much more easy to detect then mines in a highly cluttered background. Clutter is a complex phenomenon and depends largely on the spatial distribution of the background, which depends on e.g. the variation in soil , soil type, moisture content, rocks, vegetation, shadows, and illumination.
- Atmosphere: the propagation of radiation and therefore detectibility of mines depends on the atmospheric transmittance. Transmission will decrease with increasing distance, due to increasing scattering as well as increasing absorption. For small distances (e.g. 500 meters) the transmission losses in the IR are relatively small.

In case of active sensors:

- For active IR sensors instead of he apparent temperature, the difference in retro-reflectance of a mine and its background is important. The IR reflectance of a mine depends on its surface conditions (e.g. roughness), material properties (reflection coefficient) and orientation (e.g. sloping or flat). For example (not painted) metal mines can create strong retro-reflections and non-metal mines with a rough (diffuse) surface structure can be hard to detect.

- The effect of spatial resolution on the detectibility is almost the same as for passive IR systems, except that the laser-spot that is used can be smaller than the IFOV of the IR imager.
- Overall, images of active systems show less clutter then images of passive system. One of the reasons of this is that in images of active IR systems there is no clutter due to shadows because of the retro-reflectance principle of such a system. Of course also the spatial distribution of the retro-reflectance image is different from that of an image of a passive system due to the difference in illumination.
- Images of an active IR system show speckle. Speckle arises from the reflection of coherent illumination from a diffuse surface. The diffuse surface of e.g. a mine creates an array of scatterers that is independent and randomly phased. This results in contructive (bright spots) and destructive (dark spots) interference at the observation plane. As can be seen in figure 3.9, this speckle can have a large influence on the detectibility of mines and minefields.
- The effects of the atmosphere on the detection of mines is for active sensors almost the same as for passive sensors.

Table 3.11: Differences, advantages and disadvantages of active and passive TIR imaging systems for remote mine (field) detection.

	PASSIVE thermal infrared system	ACTIVE infrared system
principle:	image of scene constructed of TIR emission and reflection of the scene	image of scene constructed of retro-reflectance of the radiation of a source on the system
contrast between mine and background:	difference in apparent temperature between mine and background	difference in angular reflectance between mine and background
contrast behaviour:	contrast varies mainly due to sun illuminance, meteorological and environmental conditions	contrast between a mine and the background is constant
most common wavelength band:	MWIR, 3-5 μm LWIR, 8-12 μm	10.6 μm (CO_2 laser)
image distortion:	clutter	speckle
vulnerability:	less	greater due to complexity, possi-bility of jamming the data link
countermeasures:	more difficult: - paints: anti-reflective - modifying shapes - decoys	less difficult: - paints: anti-reflective - rough surface - changing surface orientation - decoy

Both active and passive IR systems have limitations in terms of their applications to mine and minefield detection. A system which simultaneously creates active and passive IR images would be vastly superior to either of the two individual methods.

4 SIGNAL PROCESSING TECHNIQUES

Most of the data techniques that are presented in this chapter are a summary of the techniques presented in a book on image analysis [F25], a Danish paper [F5] and some articles on morphology [F8-F24], and focus on the techniques applicable to autonomous detection of mines and minefields.

Image analysis is a multifaceted subject that deals with sensors, data analysis algorithms, dedicated processing hardware and storage devices. This chapter deals with the subject of data analysis algorithms. The purpose here is to cover the most important elements of data analysis tasks towards mine(field) detection. The principle stages involved can be categorised as:

- image enhancement
- edge detection
- segmentation
- feature extraction and classification
- morphology

The first four topics are grouped together in paragraph 4.1 since they serve as a building block for image analysis on mine detection. Morphology is treated as stand alone topic covered in paragraph 4.2.

Mines are assumed to be distributed in regular patterns, and sensors are assumed capable of creating low contrast images of a limited percentage of mines. There is no restriction on the particular kind of sensor, except that it must have an imaging capacity. It is however recognised that the particular choice of a sensor will in general have an impact on the choice of data-processing algorithm.

4.1 Image enhancement, edge detection, segmentation, feature extraction and classification

<u>Enhancement:</u>

The purpose of image enhancement is to improve image quality by employing techniques that suppress noise, de-blur object boundaries and highlight some specific features within images. Image enhancement tools help simplify those operations that normally follow the image enhancement step. Image enhancemet is also used for image processing applications in order to enhance the image appearance. For real time detection of mines by men (instead of automatic mine detection), enhancement techniques are very useful since they improve visualisation and image display.

Edge detection:
Information content in the edges of an image can reveal important object characteristics such as size and shape. Most edge detection techniques employ some type of gradient measure. Edge detection techniques for mines can very from simple models to more complex stochastic-based edge detection models. Examples of edge detection filters for mine detection are [F5]:

- gated filtering: this method is based on mean contrast difference in a variable region surrounding the targets. The result of the algorithm produces images which contains the contrast difference between the mean value of the pixel intensity in the inner window and the mean value of the intensity of the surrounding pixels in the outer window.
- local filter operator: this operator is flexible with respect to accentuating different features in images, which occurs for mines covering a small region in an image.
- inverse median filter: the general method is to replace the grey level of each pixel by the median of the grey levels in the surrounding region of pixels. This filter is particularly efficient when the noise pattern consists of strong, spikelike components, and preserves edges.
- contrast filter: with a contrast filter edges, lines (e.g. roads) as well as homogeneous areas can be suppressed.

Segmentation:
Image segmentation, the process of partitioning a digital image into regions, is important for the recognition of mines and mine-types. There are various segmentation algorithms that can classify a group of pixels with similar image properties into a mine. These can be grouped into three main categories:

- thresholding,
- edge detection,
- region growing.

Some of the above techniques are referred to as “bottom up” techniques in the sense that the image segmentation process relies on the individual grey values of pixels without using any knowledge of spatial relationships (of e.g. mines) between various structures in the image. In contrast to “bottom up techniques”, “top down” methods use information about the shape and position of regions of interest to guide the image segmentation process.

Feature extraction:
Feature extraction is one of the essential steps that follow image segmentation. Typical features for mine detection can be shape, area, colour and texture. These features can be used to classify patterns (minefield), recognise shapes (mines) or seperate suspect parts from good parts. Features can be defined to be local, global or both. Features based on only local image data can produce poor results due to image noise and poor image contrast.

4.2 Mathematical morphology

Mathematical morphology is the name for a number of image processing functions based on set theory. The fundamental theory is developed in the sixties. This theory was applicable to binary images (black-and-white images) only. It was extended for use with grey-scale images in the eighties. The (thermal infrared, radar, ...) images foreseen to be used for minefield detection are all grey-scale images: these images contain the emission, reflection, ... as a function of position. In the past the use of dedicated parallel hardware was obligatory in order to run the algorithms in a reasonable amount of time. Recently efficient sequential implementations were made, which execute fast on ordinary hardware (e.g., SUN workstations).

The most important applications of the algorithms regard:

- identification of geometrical structures (e.g., locating all circular disks).
- segmentation (e.g., splitting an image in sub-images which have approximately constant brightness).
- image enhancement (e.g., of edges as in figure 4.1).
- hierarchical decomposition (splitting an image in a set of images which represent the same information at different resolutions).

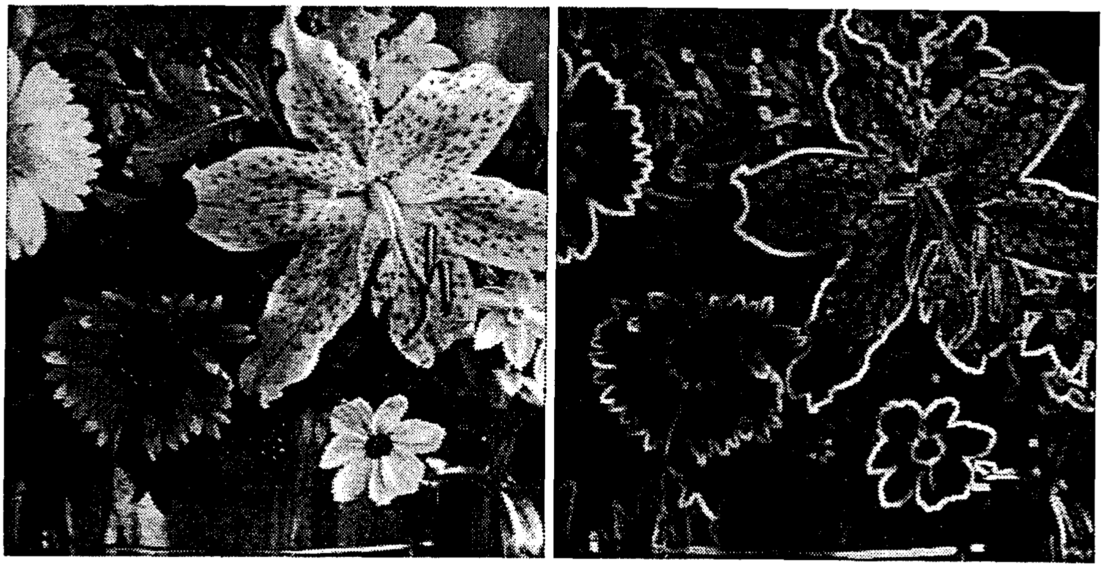

Figure 4.1: *The image to the right results from applying the morphological gradient operator (which enhances edges) to the image at the left [F16].*

To get an impression of the use of the morphological algorithms for mine(field) detection we:

- performed a small literature survey. Abstracts on this topic are in appendix F [F8-F24] of this report.
- requested for the tape with thermal imagery of a test minefield offered by Dr. R. Barnard (Fort Belvoir, chairman of RSG-1) during the December 1993 RSG-1 meeting. We got this during the June 1994 meeting.
- installed the implementation of grey-scale morphological algorithms by A. Peter's (Vanderbilt University School of Engineering, Nashville) on a SUN workstation. The algorithms will be tested on the above mentioned thermal imagery.
- made a program which creates rudimentary radar images, consisting of several geometrical shapes (block, cone, pyramid) with additive or multiplivative ("speckle") noise superimposed on it. These images were used to get an impression of what the morphological algorithms do exactly.

4.3 Minefield detection

The detection of minefields is different from the detection of separate mines. Research in UK showed that the detection of only a small amount (e.g. 40 %) of the mines in a minefield is enough to detect a minefield. The approach for the detection of minefields consists of three basic steps.

1. Initially thresholded *mine (e.g. edge) detection* filters are applied to the image data, to provide a set of candidate targets.
2. With the candidate targets, *complex geometric* structures are built by analysing the context of each candidate targets. Based on the complex structures, a target location hypothesis is constructed.
3. The input image is re-examined with the mine-detector, where the parameters are modified properly. If the target hypothesis is confirmed, the candidate target set is expanded and the procedure continues until a new target hypothesis cannot be established.

Techniques for the above points 1 and 3 are described in paragraph 4.1.

<u>Complex geometric shapes extraction:</u>

Complex shapes are characterised by geometric features. The first step is thus to provide an internal low level representation of the geometry. The next step is to formulate a hypothesis about the underlying structure of the target distribution and to test the hypothesis for confirmation or rejection.
Several methods like line building, syntactic parsing, regular array detection are already known in literature. These methods are complex, but can function well if the quality of the input image is well enough. Good examples of these methods are described in [F3, F4, F6, F7].

5 RECOMMENDATIONS

A (near) real time land mine or minefield detection capability is essential since it will enable military commanders to plan their movements to circumvent the mines (or minefields) or to allocate/employ mine neutralisation/ breaching assist to clear a safe route through the minefield.

The military benefits will include the following:

- fast mine and minefield detection
- reduced casualties and less equipment loss
- advanced planning for mine and minefield avoidance or breaches
- enhanced mobility

Results of the in chapter 3 represented (dis)advantages of imaging mine detection systems in several wave-length bands are summarised in table 5.1.

The recommendations presented in this chapter can be seen as a guideline for the initiation of possible follow-up studies. They are based on the literature survey, the main conclusions from the activities and research of the different RSG member countries and the discussions and demands of the DMKL, GEVST-MUN (project leader ing. N.L.P. de Bruyn Prince-van Kempen).

Recommendations on remote mine detection:

1. RADAR:
   The literature survey and experimental results of several member countries of the RSG indicate that conventional medium-resolution imaging radars are less suitable for remote mine detection. Probably detection of the largest (30 cm diameter) mines becomes possible for spatial resolutions below 5 cm, for certain aspect angles. The ground penetrating capability of long wavelengths makes radar one of the few candidates for buried mine detection. Characteristics and results of existing systems (e.g., which are currently used to locate buried pipe lines) should be investigated with respect to their applicability to buried mine detection.

2. MICROWAVE RADIOMETRY:
   Recent research shows that this detection principle is promising for remote mine detection. None of the RSG members are currently investigating this field, due to budgetary reasons. Research of TNO-FEL on this technique [B10-B11] would be a welcome addition to the RSG's workprogram Therefore a feasibility study at the costs, characteristics, possible applications and detection chances is recommended. This feasibility study should include measurements with a tower-based system.

Table 5.1: *(Dis)advantages of imaging systems in several wavelength bands.*

sensor			all day[1]	weather restrictions[2]	spatial resolution[2]	non-metallic more difficult[3] ?	vegetation/ ground penetration [4]	counter measures	speckle/ clutter/ shadows/ noise	real time ?	mine aspect angle dependence	system dimensions[5]
class	type	wavelength										
visual & NIR	lineair CCD with spectral filters	0.596-0.732 µm 0.734-1.238 µm 1.502-1.750 µm 1.998-2.130 µm 2.134-2.290 µm	no	rain, fog, etc.	adequate	no	none	difficult	clutter due to shadows	yes	medium	small
	active NIR laser scanner	0.6943 µm[6], 1.064 µm[7], 1.54 µm[8], 1.543 µm[9], etc.			adequate	no	none	possible with jammer	speckle noise	yes	large	small
	LLLTV	400-800 nm	yes	idem	adequate	no	none	easy (paints)	clutter due to shadows and high noise level	yes	medium	small
	aerial photography	400 nm - 1.1 µm	no	idem	adequate	no	none	idem	clutter due to shadows	no	medium	small
infrared: MWIR & LWIR	passive	3-5 µm 8-12 µm	yes	heavy rain and fog, etc.	adequate	yes	poor	difficult	clutter depends on weather conditions *)	yes	small	small
	active	10.59 µm[10], etc.	yes	idem	adequate	yes	none	possible with jammer	speckle noise	yes	medium	medium
microwave	radar	30 cm	yes	none	inadequate	yes	good	idem	idem	yes, but expensive	medium	large
		3 cm	yes	none	doubtful	yes	poor	idem	idem	idem	large	medium
		3 mm	yes	none	adequate	yes	none	idem	idem	idem	large	medium
	radiometer	3 mm	yes	none	adequate	yes	none	difficult	thermal noise, clutter as *)	yes	small	small/ medium

[1] all day means day- as well as nighttime operation possible
[2] assumptions: distance between mine and sensor system = *100* m, mine diameter = *15* cm
[3] with respect to metallic mine detection
[4] mine depth of 10 cm assumed for ground penetration
[5] small < 50 cm x 50 cm x 50 cm < medium < 1 m x 1 m x 1 m < large
[6] Ruby
[7] Nd:YAG
[8] Er:Glass
[9] Raman-Shifted Nd:YAG
[10] CO_2

3. VISUAL and NEAR INFRARED:
The characteristics of visual and near infrared imaging are often requested as addition to an imaging system active in another wavelength band. This is because imaging systems in these bands are often low cost, compact, have a high spatial resolution and can be used real time. Using these systems in combination with several well chosen spectral bands, makes is possible to even detect camouflaged, partly covered mines. A recommendation for a future follow-up is a feasibility study at the possibility of the addition of a visual and near infrared imaging system (for example a 12 bits CCD line-scanner with several filters) to another mine detection system.

4. MID-WAVE and LONG-WAVE INFRARED:
Recent research of the RSG member countries and literature survey show that the mid- or long-wave infrared wavelength band is a promising band for remote mine detection. An active thermal infrared system as well as a passive thermal infrared system have several advantages compared to those operating in other wavelength bands and most of these disadvantages can be abolished by a combination of an active and passive system. Therefore a feasibility study into a combined passive and active remote mine detection system is strongly recommended. This feasibility study should include measurements with a tower-based system.

5. SENSOR FUSION:
Shortcomings of individual wavelength bands can be reduced by combining several wavelength bands. Meteorological conditions (such as rain showers) can make mine and minefield detection in mid- and longwave infrared wavelength bands difficult. Small mines are hard to detect with a system based on radar or microwave radiometry. Detection systems that use CCD camera's active in the visual and near infrared wavelength ranges can not be used during night time. A mine(field) detection system utilizing several wavelength bands simultaneously will circumvent part or even all of these shortcomings. Therefore in future research the above mentioned feasibility studies should be combined in a way that their results can be compared and can lead to an advise on a multispectral mine(field) detection system.

6. IMAGE PROCESSING:
Even as important as a future mine detection system is the interpretation of the data of such a system. A study on the best processing techniques and a reliable and accurate interpretation of the images of a remote mine detection system has to run parallel with the development of a mine(field) detection system. Some examples of of processing techniques were presented in chapter 3.

7. FUTURE RESEARCH: The research in the Netherlands should have as main long term objective the development of a demonstrator vehicle mounted multi-sensor system. Table 5.2 provides a provisional time table for the different steps leading to such a system. Reasons for the choice of a vehicle mounted instead of a UAV based system are:
   - the "Genie" expressed its interest for a vehicle based system.

- a vehicle based system is cheaper than an UAV based one, for example because of the high datarates and necessary downlink of the latter. Research in the area of an UAV based system would be limited to only parts of it, while it seems feasible to develop a prototype vehicle based system.
- the much aclamed merrits of sensor-fusion can be tested. Candidate sensors are discussed in the above presented points 1 to 6.
- it is not covered by the current RSG work programme.

Table 5.2: Provisional time table for a vehicle mounted demonstrator.

	1995	1996	1997	1998	1999	2000	2001
feasibility study	XXXX	XX					
tower masurements	XX	XXXX	XXXX				
demonstrator design			XX	XXXX			
demonstrator construction				XX	XXXX	XX	
demonstrator tests						XXXX	XX

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APPENDIX A: ABSTRACTS ON DETECTION WITH RADAR

[A1], [B1, C1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[A2] "Imaging Of Shallow Subsurface Objects: An Experimental Investigation", T. Ozdemir, S. Roy and R.S. Berkowitz, IEEE Tr.G.&RS., May 1992, 10 pages.

- Experiment with bi-static S-band (3.5 GHz) radar under optimal conditions from 40 cm height. The main drawbacks of this kind of equipment is the disturbance by the air-ground surface (with a possible random roughness) and the (possibly inhomogeneous) subsurface medium.

[A3] "Ground-probing Radar For Plastic And Metallic Mine Detection", R.J. Chignell, journal ?, 1990 ?, 3 pages.

- Description of a portable ground-probing radar system.

[A4] "Further Studies Of A Ground Penetrating Radar For The Detection Of Buried Mines", L. Peters, Ohio State University / US Army Belvoir Research, Development And Engineering Center, July 1990, 16 pages.

- Description of a radar utilising a bi-focal offset reflector antenna. With such an antenna the radar can be used at a greater height than.conventional systems.
- Description of experiments with dummy mines.

[A5], [B2, C2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[A6] "'Lantern' Used To Find Gulf Mines", J. Boatman, Jane's Defence Weekly, 29 June 1991, p.1163.

- Underwater mine detection with laser radar.

[A7] "RF Break-through In Mine Detection", ?, 1992, Jane's Defence Weekly, 1/6 page.

- Non-metallic mine detection with a handheld ground-probing radar system.

[A8] "Mine Detection in Dry Soils Using Radar", J.V. Hanson et al., US Army Topography Engineering Center, Fort Belvoir, VA, March 17 1992, 15 pages.

- Description of experiment to detect surface laid and buried metallic/non-metallic mines with an airborne X, C and L band synthetic aperture radar (0.8 * 1.8 m resolution), in very dry soil. Outcome: mines seldom detectable, ground disturbance sometimes.

[A9], [G4] "The Detection of Buried Explosive Objects", J.E. McFee and Y. Das, DRES, Ralston, Canada, Canadian Journal of Remote Sensing, Vol.6, No.2, December 1980, pp.104-121.
- Overview and discussion of close/remote detection techniques/equipment useful for detection of buried mines: magnetometers, electromagnetic induction, electromagnetic radars, acoustic, nuclear detection, trace gas analysis, electromagnetic resonance absorption.

[A10], [G5] "Road Radar Development Project", EBA Canpolar Roadware, July 1992, 8 pages
- Folder of vehicle mounted radar used to profile road pavement structure etc.

[A11], [D7] "Remote Minefield Detection Using Infrared Laser Radar (U)", G.C. Stuart, DRES, Suffield, Canada, November 1988, 125 pages.
- Detailed description of concept laser radar systems carried by RPC's, operating at 10.6 micron wavelength. Discusses system design, simulation results, countermeasures.
- Appendices on noise, speckle, laser, detectors etc.

[A12], [C7, D8] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.
- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[A13], [B3, C8, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.
- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[A14], [E4] "Sensor fusion techniques", May 1993, 100 pages.
- Papers presented at a 1 day workshop held at TNO-FEL. Various subjects related to fusion techniques: Dempster Shafer theory, Bayesian inference, Kalman filtering, fuzzy logic.

[A15], [B4, D10, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.
- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[A16] "UK Notes to NATO RSG on Remote Detection of Minefields", M.I. Dallen, DRA, June 1993, 14 pp.

- NATO restricted.

[A17] "Scatter Mine Detection Radar Experiments", R.M. Berg (Belvoir R&D), March 1984, 21 pp.

- Describes an experiment with an electronically scanned radar to detect, discriminate and locate 155 mm rocket and artillery deployed sub-munitions (e.g., mines). Results are presented in 3D energy vs. time/velocity plots. This report is related to the feasibility study report "Radar Detection of Scatterable Mines" (F.R. Williamson et al., August 1984).

[A18] "Measurement and Analysis of L- and X-band Mine Cross Sections", A.L. Maffett and E.L. Johansen, ERIM, August 1979, 47 pp.

- An echoic chamber and outdoor test range. Measurements on 5 mine types (metal, plastic and wood). Measurements of mine above metal ground planes were not successful.
- Assuming typical background RCS's, it turns out that L-band radar (resolution area 1 m^2) cannot detect individual mines. Detection of minefields is possible in desert areas at low depression angles only.

[A19] "Radar Detection of Scatterable Mines", F.R. Williamson et al., Georgia Tech., August 1984, 223 pp.

- Feasibility study of using a ground-based tracking radar to determine the emplacement locations of scatterable mines (from measurements made during scattering). This extensive report provides target characteristics (155 mm projectiles, MLRS etc.), lab RCS measurements, a live-fire test plan and radar (design) characteristics. However, it does not contain measurement results obtained with a tracking radar. These are included in "Scatter Mine Detection Radar Experiments" (R.M. Berg, March 1984).

[A20] "Minefield Detection Using an Airborne Microwave Radar", I.P.W. Sinclair et al., MPB Technologies Inc., July 1985, 133 pp.

- Includes a literature survey on radar's and radar scattering from terrain, a sub-scale laboratory experiment and a computer simulation.
- The laboratory experiment was carried out at 34 GHz with a vertical looking radar moving at 1 meter height over a sand bed (dry, wet, smooth and rough). Numerous datasets of (scaled down) 2 and 5 cm, buried and unburied "mines" were obtained.
- It was concluded that once the footprint is sufficiently small, detection is possible. Buried mines sometimes featured higer RCS's than unburied ones.

APPENDIX B: ABSTRACTS ON DETECTION WITH MICROWAVE RADIOMETERS

[B1], [A1, C1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[B2], [A5, C2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[B3], [A13, C8, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[B4], [A15, D10, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[B5] "Microwave Radiometric Studies in Relation to Mine Detection", C.N. Johnson and D.L. Gravitte, US Army R&D laboratories, Fort Belvoir VA, November 1966, 96 pages.

- Laboratory results of measurements with a C-band (5 cm) radiometer indicated that detection of buried mines should be feasible.
- However, field measurements over clay-type soils at Fort Belvoir indicate that such a system is highly unsuitable, due to masking signals even under the most favourable (dry weather) conditions.

[B6] "Feasibility Study of Microwave Detection of Mine Fields", K.J. Keskinen et al., MPB Technologies Inc., March 1989, 95 pp.

- Follow-up of report "Minefield Detection Using an Airborne Microwave Radar" (I.P.W. Sinclair et al., July 1985). Contains an extended literature review, scaled down measurements of backgrounds and model mines.
- The main conclusion is that a down-looking (obligatory due to the specular nature of reflection by horizontal mines) active microwave system should be flown at a low height (<

100 m) and has an unacceptable small swath width of only 2 meters. It is therefore recommended to conduct a study similar to this one with a radiometric (passive) system. The results of this study are reported in "Microwave Radiometry for Minefield Detection" (MPB Technologies Inc., April 1991).

[B7] "Microwave Radiometry for Detection of Metallic Targets", K. Keskinen et al., MPB Technologies Inc. / DRES, In: Proc. of Spec. Meeting on Microw. Radiometry and Rem. Sens. Appl., 1992, 5 pp.

- Series of experiments with roof-mounted 35 and 90 GHz radiometers used to detect uncovered metallic mines.
- Conclusions: detection is possible at both frequencies at beam fill factors (= mine area divided by antenna footprint) down to 0.1, at any incidence angle up to 70 degrees (the target contrast temperature is independent of this angle). The 0.1 lower limit was determined by system noise. If system noise is negligible, natural variations of terrain apparent temperature will set the lower limit. Other targets (plastic mines, rocks, pieces of wood) were not detectable unless the beam fill factor was in the order of unity. This article is a summary of the report "Microwave Radiometry for Minefield Detection" (MPB Technologies Inc., April 1991).

[B8] "Microwave Radiometry for Minefield Detection", MPB Technologies Inc., April 1991, 62 pp.

- A summary of this report is the article "Microwave Radiometry for Detection of Metallic Targets" (K. Keskinen et al., 1992). An additional observation was that plastic mines could be detected down to beam fill factors 0.2 at 35 GHz. A helicopter-borne version of this system would have a weight of 70 kg and volume of L*W*H= 0.8*0.5*0.4 m^3, respectively, and should be flown at 30 km/hour at a height of 15 m.

[B9] "A Feasibility Study of Radiometry as a Sensor for Military Applications", J. Snieder and W. Keizer (TNO-PML), March 1981, 78 pp.

- Introductory text about microwave radiometry, based on a literature survey. Contains elementary material about practical aspects, like the impact of antenna choice, weather conditions, frequency choice etc. The range equation is used to determine the feasibility of detection of airplanes, persons, ships, tanks etc. Only the detection of airplanes seems impossible. The text ends with a discussion of the (dis)advantages of microwave radiometry.

[B10] "Initial Results in the Development of a Synthetic Aperture Microwave Radiometer", D.M. Le Vine et al., IEEE Tr. on Geosc. and RS., July 1990, 6 pp.

- This L-band (1.4 GHz) airborne synthetic aperture radiometer utilizes an antenna consisting of several sticks, aligned along-track. Along-track resolution is determined by the length of the sticks, while the across-track resolution is determined by the largest distance between two sticks (this is called the synthetic aperture length. For SAR the synthetic aperture is much larger than the physical aperture size). An advantage over a real aperture system is that there is no need to scan the surface in across-track direction to obtain a large swath width. First measurement results demonstrate the valididity of the concept.

[B11] "The Sensitivity of Synthetic Aperture Radiometers for Remote Sensing Applications from Space", D.M. Le Vine, Radio Science, July-August 1990, 13 pp.

- The synthetic aperture antennas discussed consist of a collection of spaced (small) antenna. Synthetic aperture radiometers do not scan cross-track like real aperture systems do. Cross-track image formation is accomplished by processing the data from different antenna pairs with different spacings, instead. The highest (best) spatial resolution is approximately the same as that of an antenna with equal physical dimensions. The radiometric resolution is only marginally worse than that of a real aperture system. A detailed analysis is presented of several synthetic antenna configurations, with the emphasis being on spaceborne remote sensing systems.

APPENDIX C: ABSTRACTS ON DETECTION WITH VISUAL AND NIR SENSORS

[C1], [A1, B1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[C2], [A5, B2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[C3], [D4] "Stand-off Minefield Detection Systems (STAMIDS) Advanced Technology Transition Demonstration (ATTD)", K.G. Hall et al., The Military Engineer, August 1991, 2 pages.

- STAMIDS: sensor in an ULV, data transmitted to ground station, real-time image processing for minefield detection. Description of ATTD phase 1 test September October 1990. Flights over 2530 minefields, two times per day for 3 weeks.
- Sensors: AMIDARS = infrared airborne scanner; REMIDS = optical scanner in helicopter, 3 channels: two active laser polarisation/reflectance, one passive infrared; CMADS = thermal helicopter borne thermal infrared.

[C4], [D5] "Mine/Countermine Research", H.W. West et al., The Military Engineer, August 1985, 3 pages.

- Stand-off detection: high resolution photography, thermal line scanner, multi-frequency optical data. Neutralisation: MICLIC, mine response model. Mine use: wide-area mines etc.

[C5], [D6] "The MIDURA 19821983 Experimental Test Plan", D. Griffith and Y. Morita, ERIM, Michigan, April 1982, 67 pages.

- Detailed test plan (no results) for one year of flights with optical and thermal infrared cameras over areas with buried and surface laid AT minefields.

[C6] "Analysis of Aerial Photography From Array II (1980)", M.B. Walsh, ERIM, Michigan, May 1982, 23 pages.

- Results of AT mine detection experiment with airborne cameras. Contains summary of ARRAY I (conducted July August 1979) results.
- Results: ARRAY I mines better detectable (no magnification necessary) than ARRAY II (magnification necessary).

- Possible causes: different background homogeneity, sun elevation angles/specular reflections, vegetation type. Shadows are the most important detection cue, so direct sunlight is important. Specular reflections are also important.
- Array I: surface laid mines are detectable, buried mines also due to ground disturbances (like furrows).

[C7], [A12, D8] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.

- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[C8], [A13, B3, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[C9] "Preliminary Investigations of a High Spectral Resolution Imaging Spectrograph (CASI) for Detection of Surface Scattered Land Mines", R.J. Soofer and J. McFee, ?, 1992 ?, pp. 487-492

- Measurements with a CASI (wavelengths 425-925 nm) operated from a horizontal scanning manlift (cheap compared to aircraft) on natural targets and five Warsaw Pact type mines.
- The mine spectra differ from those of natural targets, suggesting suitability of the CASI for mine detection.

[C10], [D16] "Final Report on a Study of Visible and Infrared Mine Field Detection", Barringer Research Limited, July 1985, 180 pp.

- Presents a general overview based on a literature search, and own work. The latter includes analyses of mine and terrain visible and near infrared (VNIR) spectra, and thermal modelling of buried mines. Main conclusions:
    - in the visible and near infrared bands detection of mine like objects occupying > 20 percent of the pixel area is possible for most terrain types.
    - to discriminate mines from the terrain a minimum of 3 VNIR spectral channels of high spatial resolution is necessary.
    - computer modelling revealed the feasibility of detecting a buried iron layer at depths of up to 20 cm by remote sensing of ground surface temperate anomalies. Vegetation layers greatly reduce this possibility.
- Contains 350 references.

APPENDIX D: ABSTRACTS ON DETECTION WITH MWIR AND LWIR

[D1], [A1, B1, C1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.
- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[D2] "Sensor Fusion Methodology For Remote Detection Of Buried Land Mines", N.D. Grande, Lawrence Livermore National Laboratory, Livermore, April 1990, 21 pages.
- Two channel passive IR system (5 and 10 micron), 60 m height, 0.2 K temperature resolution. Description of (buried) mine detection experiment. It is made plausible that two channel systems have a superior performance compared to one channel systems.

[D3], [A5, B2, C2, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.
- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[D4], [C3] "Stand-off Minefield Detection Systems (STAMIDS) Advanced Technology Transition Demonstration (ATTD)", K.G. Hall et al., The Military Engineer, August 1991, 2 pages.
- STAMIDS: sensor in an ULV, data transmitted to ground station, real-time image processing for minefield detection. Description of ATTD phase 1 test September October 1990. Flights over 2530 minefields, two times per day for 3 weeks.
- Sensors: AMIDARS = infrared airborne scanner; REMIDS = optical scanner in helicopter, 3 channels: two active laser polarisation/reflectance, one passive infrared; CMADS = thermal helicopter borne thermal infrared.

[D5], [C4] "Mine/Countermine Research", H.W. West et al., The Military Engineer, August 1985, 3 pages.
- Stand-off detection: high resolution photography, thermal line scanner, multi-frequency optical data. Neutralisation: MICLIC, mine response model. Mine use: wide-area mines etc.

[D6], [C5] "The MIDURA 19821983 Experimental Test Plan", D. Griffith and Y. Morita, ERIM, Michigan, April 1982, 67 pages.
- Detailed test plan (no results) for one year of flights with optical and thermal infrared cameras over areas with buried and surface laid AT minefields.

[D7], [A11] "Remote Minefield Detection Using Infrared Laser Radar (U)", G.C. Stuart, DRES, Suffield, Canada, November 1988, 125 pages.

- Detailed description of concept laser radar systems carried by RPC's, operating at 10.6 micron wavelength. Discusses system design, simulation results, countermeasures.
- Appendices on noise, speckle, laser, detectors etc.

[D8], [A12, C7] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.

- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[D9], [A13, B3, C8, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[D10], [A15, B4, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[D11] "Infrared Reflectance Measurements of Replica Mines and Reference Targets", G.C. Stuart, DRES, Canada, February 1989, 39 pages.

- Presents 10.6 micron reflectance data of replica mines which have been found to be specular (mirror-like) at thermal IR wavelengths, although with a substantial variation in the magnitudes of the returns. This means that such a sensor must be downward-looking and only those mines within a fairly small angular field of view will give significantly large reflected signals.

[D12] "Site Characterisation for Remote Minefield Detection Scanner (REMIDS) System Data Acquisition", K.S. Long and K.G. Hall, USAE Waterways Experiment Station, Vicksburg MS, April 1991, 107 pages.

- Description of study to collect ground truth data from various target arrays in several backgrounds under various environmental conditions to evaluate REMIDS (which uses both passive thermal and active 10.6 micron laser detector arrays). Ground data measured included surface geometry, vegetation parameters, on-site meteorology etc. Mines used: RAAM, M15 and M19. Several flights were performed in both the summer and fall seasons.

[D13], [E2] "Simulation of images by photometric stereo modelling", K.L. Russell, J.E. McFee and M.R. Ito, Optical Engineering, 30(9), September 1991, pp. 1337-1346

- Presents a method to synthesise images resembling those measured by an airborne sensor. Method: create model scene (e.g., from clay with dimensions 10*10 cm) add surface type dependent texture, digitise model under different illumination directions, create depth map with photometric stereo method, compute image from depth map, tables of reflectivity/emissivity data (for each surface type) and flight geometry parameters, add noise > synthetic image.
- Emphasis is on (validation of) the photometric stereo method.
- The photometric stereo method is validated with computer generated images of a bi-variate normal and hemispherical shape. In addition, a real clay-coated hemisphere model is used.
- Finally, the whole algorithm is used to generate a synthetic image of a terrain with landmines in it, mimicing the output of an ideal pushbroom scanner using a 10.6 micron laser.

[D14], [E4] "Computer Vision for Locating Buried Objects", G.A. Clark et al., ?, December 1992 ?, 5 pages

- Experiment with 9-14 inch deep buried surrogate 612 inch diameter mines. The field consisted of sandy-loam covered by grass. Analysis of (ratios of) 5 and 10 micron IR images using Gabor transforms, a neural network etc. results in semiautomatic detection of 6 of the mines.

[D15] "Analysis and Trial of an active longwave infrared imaging system for minefield detection and identification", Jean R. Simard, November 1992, 66 pp.

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[D16], [C10] "Final Report on a Study of Visible and Infrared Mine Field Detection", Barringer Research Limited, July 1985, 180 pp.

- Presents a general overview based on a literature search, and own work. The latter includes analyses of mine and terrain visible and near infrared (VNIR) spectra, and thermal modelling of buried mines. Main conclusions:
  - in the visible and near infrared bands detection of mine like objects occupying > 20 percent of the pixel area is possible for most terrain types.
  - to discriminate mines from the terrain a minimum of 3 VNIR spectral channels of high spatial resolution is necessary.
  - computer modelling revealed the feasibility of detecting a buried iron layer at depths of up to 20 cm by remote sensing of ground surface temperate anomalies. Vegetation layers greatly reduce this possibility.
- Contains 350 references.

[D17], "Introduction to electro-optical imaging and tracking systems", Khalil Seyrafi, S.A. Hovanessian, Artech House, Boston, London, 1993, 260 pp. ISBN 0-89006-672-8

- Presents a general overview on the most resent EO-techniques. Ten capters dealing with respectively 1.Historical development; 2.Optical radiation; 3.Atmospheric transmission; 4.Spectral, Spatial, and Temporal Variations in Infrared Backgrounds; 5.Detection and Discrimination in EO Sensors; 6.EO System Design and Performance Equations; 7. EO Systems Applications; 8.Laser Radar Systems

[D18], "The Infrared & Electro-Optical Systems Handbook, Volume 4: Electro-Optical Systems Design, Analysis, and Testing", Michael C. Dudzik, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 352 pp., ISBN 0-8194-1072-1

- System design, analysis, and testing, including adjunct technology and methods such as trackers, mechanical design considerations, and signature modelling. Six chapters containing respectively: 1.Fundamentals of EO Imaging Systems Analysis; 2. EO Imaging System Performance Prediction; 3.Optimechanical Design; 4.Infrared Imaging System Testing; 5. Tracking and Controling Systems; 6. Signature Prediction and Modelling

[D19], "The Infrared & Electro-Optical Systems Handbook, Volume 5: Passive Electro-Optical Systems", Stephen B. Campana, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 356 pp., ISBN 0-8194-1072-1

- Contempary infrared passive systems such as FLIR's, IRST's, IR line scanners, and staring array configurations. Four chapters containing respectively: 1.Infrared Line Scanning Systems; 2. Forward-Looking Infrared Systems; 3.Staring-Sensor Systems; 4.Infrared Search and Track Systems

[D20], "The Infrared & Electro-Optical Systems Handbook, Volume 6: Active Electro-Optical Systems", Clifton S. Fox, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 312 pp., ISBN 0-8194-1072-1

- Active systems including mostly new material on laser radar, laser range finders, millimeter-wave systems, and fiber optic systems. Four chapters containing respectively: 1.Laser Radar; 2. Laser Rangefinders; 3.Milimeter-Wave Radar; 4.Fiber Optic Systems

APPENDIX E: ABSTRACTS ON MULTISPECTRAL DETECTION

[E1], [A1, B1, C1, D1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[E2], [A5, B2, C2, D3, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[E3], [A13, B3, C8, D9] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[E4], [A14] "Sensor fusion techniques", May 1993, 100 pages.

- Papers presented at a 1 day workshop held at TNO-FEL. Various subjects related to fusion techniques: Dempster Shafer theory, Bayesian inference, Kalman filtering, fuzzy logic.

APPENDIX F: ABSTRACTS ON DATA PROCESSING

[F1], [A5, B2, C2, D3, E2] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[F2], [D13] "Simulation of images by photometric stereo modelling", K.L. Russell, J.E. McFee and M.R. Ito, Optical Engineering, 30(9), September 1991, pp. 1337-1346

- Presents a method to synthesise images resembling those measured by an airborne sensor. Method: create model scene (e.g., from clay with dimensions 10*10 cm) add surface type dependent texture, digitise model under different illumination directions, create depth map with photometric stereo method, compute image from depth map, tables of reflectivity/emissivity data (for each surface type) and flight geometry parameters, add noise > synthetic image.
- Emphasis is on (validation of) the photometric stereo method.
- The photometric stereo method is validated with computer generated images of a bi-variate normal and hemispherical shape. In addition, a real clay-coated hemisphere model is used.
- Finally, the whole algorithm is used to generate a synthetic image of a terrain with landmines in it, mimicing the output of an ideal pushbroom scanner using a 10.6 micron laser.

[F3] "A classifier for feature vectors whose prototypes are a function of multiple continuous parameters", J.E. McFee and Y. Das, IEEE Tr. on Pattern Analysis and Machine Intelligence, 10(4), July 1988, pp. 599-606.

- Describes a classification algorithm suited to the problem of assigning classes and in addition (a) continuous parameter(s), based on measured feature vectors. The algorithm is tested on computer generated magnetic dipole moments (sometimes including noise) which are used as feature vectors to classify a set of 6 homogeneous different sized ferrous spheroids (models for artillery shells) and their orientation (3 continuous parameters) placed in the Earth's magnetic field. The results are generally better than those of the nearest mean vector, Fisherpairwise, 1NN and Parzen classifiers.

[F4], [D14] "Computer Vision for Locating Buried Objects", G.A. Clark et al., ?, December 1992 ?, 5 pages

- Experiment with 9-14 inch deep buried surrogate 612 inch diameter mines. The field consisted of sandy-loam covered by grass. Analysis of (ratios of) 5 and 10 micron IR images using Gabor transforms, a neural network etc. results in semiautomatic detection of 6 of the mines.

[F5] "Techniques for the Detection of Land Mine Fields, Using Imaging Sensors" (draft), C.M. Birkemark and P.G. Jensen, Danish Defence Research Establishment, December 1993, 10 pp.

- Describes some data processing techniques applicable to mine (field) detection. Tow levels: isolated spot (mine) detection, followed by aggregation into lines or complex shapes. There are no tests on real data included.

[F6] "Detection of Surface-laid Minefields Using a Hierarchical Image Processing Algorithm", J.E. McFee et al., SPIE Appl. of Dig. Im. Proc., 1991, 11 pp.

- Outline of algorithm: raw data > pre-processing (correct image imperfections) > target cueing (reject regions without mines) > target shape analysis (recognise mine shaped objects) > target spatial analysis (recognise mine fields) > user.
- Generally, the data rate decreases while the algorithm complexity increases along this chain.
- The algorithm was implemented and tested up to and including the "target shape analysis" step on synthetic ***10600*** nm images. It detected reliably and consistently the mines present, although not in real time. Real time implementation is feasible.

[F7] "Analysis of Minefield Images Using a Transputer Network", J.E. McFee et al., Transp. Res. & Appl., 1993, 17 pp.

- Detailed description of transputer implementation of several stages of a multi-stage minefield detection algorithm.
- Outline of algorithm: raw data > pre-processing (correct image imperfections) > target cueing (reject regions without mines) > target shape analysis (recognise mine shaped objects) > target spatial analysis (recognise mine fields) > user.
- The two stages covered are target cueing and target shape analysis. Estimated costs for the complete network are 100 kUS$.

[F8] "Introduction to Mathematical Morphology", J. Serra, Computer Vision, Graphics, and Image Processing, 1986, pp. 283-305

- Average complex mathematically oriented introduction to the subject of binary mathematical morphology. Describes (almost) all morphological operations. Gives a few examples.

[F9] "Application of Morphological Transformations to the Analysis of Tw-Dimensional Eletrophoretic Gels of Biological Materials", M.M. Skolnick, Computer Vision, Graphics, and Image Processing, 1986, pp.306-332

- Discusses the example of the title in a concise clear way, with a minimal mathematical explanation. Morphological fiters are user to get rid of background, streak and random noise contamination, a.o..

[F10] "Grayscale Morphology", S.R. Sternberg, Computer Vision, Graphics, and Image Processing, 1986, pp.333-355

- Extension of binary morphology to greyscale morphology. Includes a noise removal example. Ends with a discussion of greyscale homotopy.

[F11] "Automatic Screening of Cytological Specimens", F. Meyer, Computer Vision, Graphics, and Image Processing, 1986, pp. 356-369

- Application of binary and greyscale morphology to the automatic screening of cytological specimens. Multi stage algorithm, using several different morphological operators.

[F12] "Morphological Structuring Element Decomposition", X. Zhuang and R.M. Haralick, Computer Vision, Graphics, and Image Processing, 1986, pp. 370-382

- Mathematical treatment of decomposition. Decomposition is needed to implement morphological transformations in a pipelined machine.

[F13] "Automated Basin Delineation from Digital Elevation Models using Mathematical Morphology", P.J. Soille and M. Ansoult, Signal Processing, 1990, pp. 171-182

- Automatic extraction of basin boundaries from a DEM, using morphological operations. The result compares well with ground survey results.

[F14] "Watersheds in Digital Spaces: An Efficient Algorithm Based on Immersion Simulations", L. Vicent and P. Soille

- Presents a fast (computation time proportional to the number of pixels) algorithm to compute watersheds in digital grayscale images. Applications to image segmentation and a DEM are included.

[F15] "Morphological Algorithms", L. Vincent, in "Mathematical Morphology in Image Processing", editor E. Dougherty, September 1992

- Presents pseudo code for the efficient implementation of several morphological operations: distance function, granulometry function, geodesic reconstruction, skeleton, watershed. Includes example applications.

[F16] "Mathematical Morphology: a Geometrical Approach in Image Processing", H.J.A.M. Heijmans, Nieuwe Archief voor Wiskunde, November 1992

- Highly mathematical treatment of several morphological operations. Contains nevertheless some clear examples.

[F17] "An Overview of Morphological Filtering", J. Serra and L. Vincent, Circuits Systems Signal Processing, January 1992, pp. 47-108

- Tutorial overview of mnorphological filtering, including the mathematical foundation. Contains a clear description of the application to the segmentation of grayscale images (pp. 86-89).

[F18] "Morphological Tranformations of Binary Images with Arbitrary Structuring Elements", L. Vincent, Signal Processing, January 1991, pp. 3-23

- Describes a fast algorithm for morphological transformations with arbitrary structuring elements. Contains pseudo code.

[F19] "Morphological Systems for Multidimensional Signal Processing", P. Maragos and R. Schafer, Proc. of the IEEE, April 1990, pp. 690-710

- Review paper. Includes sections on rank-order noise filtering (which is a generalization of median filtering), multiscale openings/closins, edge/line enhancement, detection, skeleton transformations and fractals.

[F20] "Image Analysis Using Mathematical Morphology", R.M. Haralick, S.R. Sternberg and X. Zhuang, IEEE Tr. on PAMI, July 1987, pp. 532-550

- Very readable introduction on the subject. Gently introduces the binary dilation, erosion, opening and closing operations. This is extended to their greyscale counterparts.

[F21] "Analysis of Remotely Sensed Imagery Using Digital Morphology", F.W. Rohde, NASA STAR Technical Report Issue 21, 1988, 10 pages

- Very simple introduction to binary morphology. Gives examples of dilation, erosion and the hit-or-miss transforms. Only scratches the surface of the application to remote sensing.

[F22] "Three Dimensional Morphology for Target Detection", T.J. Patterson, SPIE Vol. 1471, 1991, pp. 358-368

- Gives first a clear, pictorial introduction into three-dimensional (grey-scale) morphology. Compares a target detection system including morphological filters to one without, with SAR data as input. The morphological (non-morphological) detector provides a 93 % (70 %) detection probability at a false alarm rate of 0.6 (200) per unit area.

[F23] "Some Applications of Mathematical Morphology to Range Imagery", J.G. Verly and T.R. Esselman, International Electronic Imaging Exposition and Conference, 1988, pp. 280-285

- Short (2 text pages), heavily illustrated article on the application to LIDAR imagery and synthetic imagery. Applications are noise removal, appendage extraction and corner extraction.

[F24] "Tutorial on Advances in Morphological Image Processing and Analysis", P. Maragos, Optical Engineering, July 1987, pp. 623-632

- A review of some recent advances in the theory and applications of morphological image analysis. Applications touched are noise suppression, edge detection, region filling, skeletonization, smoothing etc. Contains 3 clear tables summarizing the definition of set-processing, function-processing and function/set-processing filters.

[F25] “Advances in Image Analysis”, Y. Mahdavieh, R.C. Gonzalez, SPIE Optical Engineering Press, Bellingham, Washington , USA, 1992, 557 pp., ISBN 0-8194-1047-0

- A review of recent advances in image analysis. The main areas covered are image enhancement, edge detection, image segmentation, feature extraction, morphology, motion analysis and industrila applications.

APPENDIX G: ABSTRACTS ON CLOSE-IN DETECTION

[G1] "Advances In The Detection Of Landmines", J.E. McFee en Y. Das, DRES, Suffield, Canada, October 3 1991, 83 pages.

- Close-in detection: methods to detect explosives (microwave resonant absorption, nuclear radiation, trace gas detection, biochemical detection); methods to detect the casing (magneto-static, E.M. induction, impedance topography, E.M. radar, acoustical, optical). Remote detection not covered.

[G2] "Close-In Mine Detection", W. Comeyne, US Army Belvoir RD & E. Center, 1991 ?, 17 pages.

- Sheets about close-in mine detection.

[G3], [H3] "Land Mines and Countermeasures; the Continuing Duel", T.J. O'Malley, Armada International 6/1990, 5 pages.

- Describes several mine types and clearance methods: metal detector, Giant Viper, ploughs/rollers/flails, Vehicle Magnetic Signature Duplicator (neutralises magnetic influence mines) etc.

[G4], [A9] "The Detection of Buried Explosive Objects", J.E. McFee and Y. Das, DRES, Ralston, Canada, Canadian Journal of Remote Sensing, Vol.6, No.2, December 1980, pp.104-121.

- Overview and discussion of close/remote detection techniques/equipment useful for detection of buried mines: magnetometers, electromagnetic induction, electromagnetic radars, acoustic, nuclear detection, trace gas analysis, electromagnetic resonance absorption.

[G5], [A10] "Road Radar Development Project", EBA Canpolar Roadware, July 1992, 8 pages

- Folder of vehicle mounted radar used to profile road pavement structure etc.

[G6] "Vapour measurements above buried land mines. Model experiments using methyl 14C TNT", M.S. Nieuwenhuizen et al., J. Energ. Mat. 8, 1990, pp.256-307.

- On close-in detection of mines by detection of vapour of explosives. Measurement results.

[G7] "Detection of clandestine explosives", M.S. Nieuwenhuizen, TNO-PML, The Netherlands, 31 pages.

- Describes several methods for close-in detection of explosives (X-Ray detection, neutron detection, RF resonance, vapour detection, mass spectrometry etc.). Contains 12 page reference list.

APPENDIX H: ABSTRACTS ON OTHER DETECTION TOPICS

[H1], [A1, B1, C1, D1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[H2] "Activity Fields Of The Electronic Equipment Service", DGA, June 1992, 16 pages.

- Sheets about remote mine detection, partially in French.

[H3], [G3] "Land Mines and Countermeasures; the Continuing Duel", T.J. O'Malley, Armada International 6/1990, 5 pages.

- Describes several mine types and clearance methods: metal detector, Giant Viper, ploughs/rollers/flails, Vehicle Magnetic Signature Duplicator (neutralises magnetic influence mines) etc.

[H4] "Land Mine Warfare Recent Lessons And Future Trends", Maj. J.R. Wyatt, 1989, 6 pages.

- Summary of mine laying and clearance techniques.

[H5] "Land Mines Cheap And Effective Area denial", M. Hewish, International Defence Review, 8/1986, pp. 1085-01091.

- Article with details about AT/AP mine types and deployment methods.

[H6] "UDT '91, a diversity of technology", D. Foxwell, International Defence Review 6/1991, p.649.

- Underwater mine detection with sonar.

[H7] "Mined Where You Go", W. Fowler, Defence, September 1990, 4 pages.

- Description of all kinds of AT/AP mines with different fuses and working mechanisms.

[H8] “Belvoir Developing Countermine Technologies”, Gayle Peterson, Army RD & Acquisition Bulletin, September, October 19888, pp. 20-21

- Mostly about mine neutralisation (MICLIC etc.)

[H9], [A15, B4, D10] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[H10] "Cambodja bezaaid met mijnen" (in Dutch), H. van Zwet, Defensiekrant page 5, February 1993, 1 page.

- About UN mission which aims at learning Cambodians how to clear local minefields.

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an overview of techniques

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

A near real time land mine(field) detection system is essential for military commanders to enable them to circumvent the mines, or to allocate/employ mine neutralisation/breaching assist to clear a safe route through a minefield.
Basic principles and strengths and weaknesses of such a system with visual, near infrared, midwave infrared, longwave infrared, microwave radiometric and radar sensors are presented.
Recommendations for a vehicle mounted multi-sensor demonstrator system are given since the "Genie" expressed its interest in such a system, it is cheaper than an aircraft mounted system and because sensor fusion can be tested and applied relatively easy on such a system.
Promising techniques for a vehicle mounted detection system are:
1. passive and active infrared imaging,
2. microwave radiometry,
3. passive and active visual and near infrared wavelength discrimination,
4. radar ground and vegetation penetration.
Proposed steps in the development of a vehicle mounted mine detection demonstration system are a feasibility study, tower measurements and design, construction and testing of the demonstrator.

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Mine detection	Infrared mine detection
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